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DIGITAL TWINS: ENGINEERING AND SIMULATION IN PULMONOLOGY

Bakhrom E. Yuldashev - associate professor
Yuldash N. Islamov - associate professor
Abdumovlon Y. Islomov
Tashkent State Medical University (Tashkent, Uzbekistan)
baxrom@rambler.ru

Abstract: *The article discusses the possibilities of applying the concept of digital twins for modeling and analyzing the functioning of the human respiratory system. The relevance of the study is due to the active development of digital medicine and the need to create personalized computational models of human organs that allow predicting the course of diseases and optimizing treatment methods. Particular attention is paid to the use of mathematical modeling methods, computational hydrodynamics, and artificial intelligence technologies to construct a digital twin of the lungs based on the patient's clinical and physiological data.*

A conceptual architecture for a digital twin of the respiratory system is proposed, combining an anatomical model of the bronchial tree, a model of lung ventilation, a biomechanical model of lung tissue, and a model of gas exchange. To formalize the functioning of the respiratory system, a mathematical model of a digital twin of the lungs has been developed, describing the relationship between air flow parameters, pressure, tissue deformation, and respiratory gas diffusion processes. A computational algorithm for constructing a digital twin of a patient is presented, allowing the integration of medical imaging data, physiological monitoring, and intelligent data analysis. The results obtained demonstrate the promise of using digital twins in pulmonology for modeling lung ventilation and developing clinical decision support systems.

Keywords: *digital twins, digital medicine, pulmonology, mathematical modeling, lung ventilation, pulmonary tissue biomechanics, computational fluid dynamics, artificial intelligence, digital patient twin, personalized medicine.*

Introduction.

In recent decades, the rapid development of digital technologies has had a significant impact on the transformation of healthcare systems around the world. The integration of artificial intelligence, mathematical modeling, big data analysis, and high-performance computing is forming a new paradigm in medical science: digital medicine, focused on personalized diagnostics, disease progression prediction, and optimization of therapeutic decisions. One of the most promising areas in this field is the concept of digital twins—dynamic virtual models of biological systems capable of reproducing the physiological processes of the body based on real clinical and biomedical data from patients [4].

In a medical context, a digital twin is an integrated computational model that combines medical imaging data, physiological parameters, clinical indicators, and machine learning algorithms to create a personalized virtual copy of a patient's organ or organism. Such models allow for computer simulations of physiological processes, analysis of the dynamics of pathological changes, and prediction of the body's response to various therapeutic interventions without directly affecting the patient. In this regard, digital twin technology is considered one of the key tools for the development of precision medicine and digital clinical decision support systems [9].

The use of digital twins is particularly relevant in pulmonology, where the functioning of the respiratory system is characterized by a high degree of complexity and multi-level organization. The lungs are a hierarchical anatomical and functional structure that includes a branched system of

airways, alveolar structures, and an extensive vascular network that supports ventilation and gas exchange processes. The development and progression of diseases such as chronic obstructive pulmonary disease, bronchial asthma, pneumonia, and acute respiratory distress syndrome are accompanied by complex changes in respiratory mechanics, ventilation-perfusion ratios, and regional lung ventilation. Traditional methods of diagnosis and clinical monitoring often do not allow for a full assessment of the dynamics of these processes, which necessitates the use of modern methods of computational modeling of the respiratory system [5].

Modern advances in medical imaging (computed tomography, magnetic resonance imaging), computational fluid dynamics (CFD), biomechanical modeling, and machine learning algorithms make it possible to create highly accurate virtual models of the lungs. The integration of these technologies into the concept of digital twins makes it possible to simulate airflows in the airways, analyze the mechanical properties of lung tissue, and predict ventilation distribution in different parts of the lungs. Such approaches open up new prospects for the development of personalized respiratory therapy strategies, optimization of ventilation support parameters, and prediction of the course of respiratory diseases [2,3].

The relevance of developing digital technologies in medicine is particularly increasing in the context of the modernization of the healthcare system in the Republic of Uzbekistan, where a number of state programs aimed at introducing digital solutions and innovative technologies into medical practice have been implemented in recent years. As part of national strategies for the development and digital transformation of healthcare, special attention is being paid to the development of medical information systems, telemedicine, artificial intelligence systems, and scientific research in the field of biomedical technologies. Respiratory diseases remain one of the most significant medical and social problems, due to both epidemiological factors and the impact of the region's environmental conditions. In this regard, the introduction of digital modeling methods and digital twin technologies can contribute to improving the accuracy of diagnosis, monitoring the condition of patients, and increasing the effectiveness of treatment for respiratory diseases [1].

Thus, the development of engineering methods for creating digital twins of the respiratory system and their application in pulmonology is a promising direction in modern biomedical science. The use of computational models and digital simulations allows for a deeper study of the physiological mechanisms of breathing, the prediction of the development of pathological processes, and the development of new approaches to personalized treatment of lung diseases. In the context of the active digitalization of the healthcare system in the Republic of Uzbekistan, these technologies can become an important tool for improving the quality of medical care and developing innovative areas of medical research.

Materials and methods.

This study used an interdisciplinary approach combining methods of biomedical engineering, computational biomechanics, medical imaging, and computer modeling to develop a conceptual model of a digital twin of the human respiratory system. The methodological basis of the study is based on modern approaches to the construction of virtual physiological systems, allowing the integration of patient clinical data, mathematical models, and computational algorithms into a single digital environment [4].

The research is **theoretical, modeling, and analytical in nature** and aims to systematize modern methods for creating digital twins of the lungs used in pulmonology. As part of the work, an analysis of scientific literature devoted to digital twins of human organs [4,9], computer modeling of the respiratory system [2,5,12,13], and the application of computational fluid dynamics in medical research [2,5] was conducted.

The methodological structure of the study included the following stages:

1. **A systematic analysis** of **scientific publications** on digital twins in biomedicine and pulmonology [1 - 13].

2. **Identification of key engineering methods** used in the construction of digital models of the respiratory system [2, 5, 10, 12, 13].

3. **Formation of a conceptual architecture for a digital twin of the lungs,** including data sources, computational models, and mechanisms for synchronization with real physiological parameters [4, 7, 8].

4. **Analysis of the possibilities of using digital models** for the diagnosis, prediction, and optimization of treatment of respiratory system diseases [3, 5, 7, 9, 11].

This approach made it possible to integrate existing scientific developments into a unified methodological model of a digital twin of the human respiratory system.

The formation of digital models of the respiratory system is based on the integration of various types of medical and physiological data. The following data categories were considered in this study:

1. **Medical imaging data.** Computed tomography (CT) and magnetic resonance imaging (MRI) data are the basis for constructing anatomical models of the lungs (Fig. 1). These methods allow for the acquisition of high-precision three-dimensional images of the respiratory tract, including the trachea, bronchi, and alveolar structures. Geometric models of the respiratory system used in further computational calculations are formed based on the segmentation of such images.

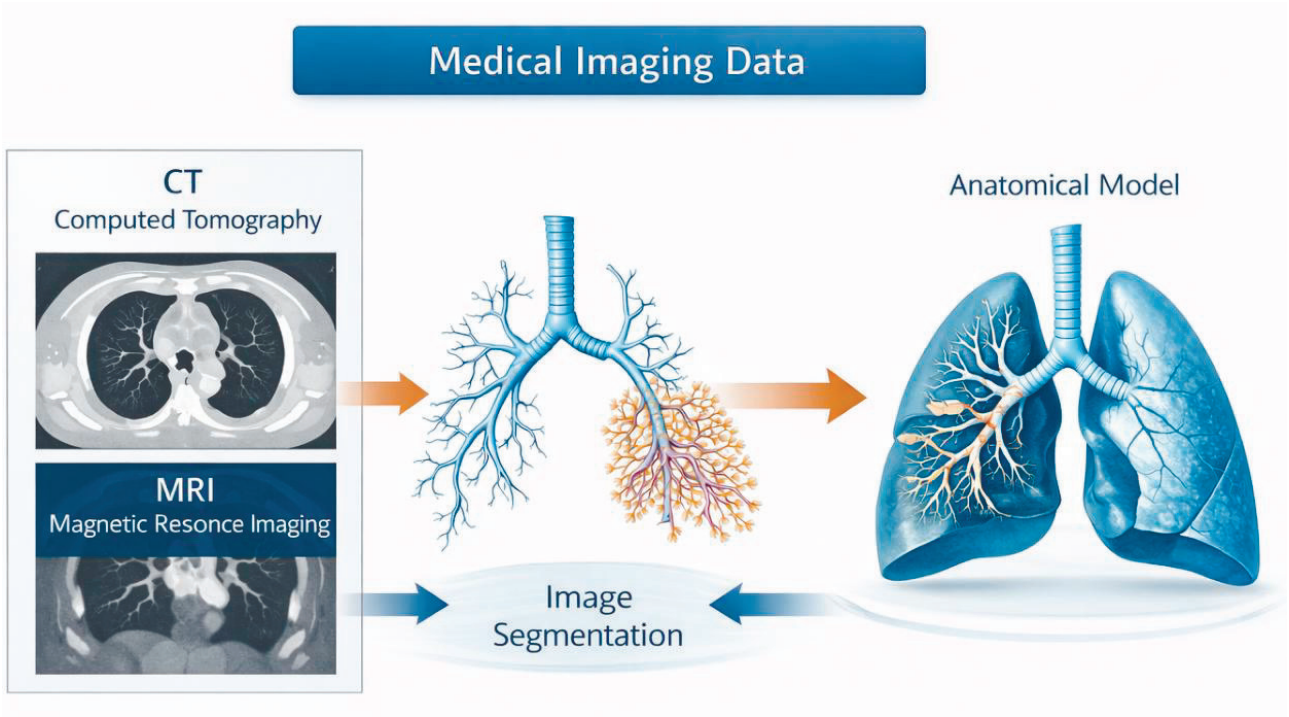


Fig. 1. Medical imaging data

2. Physiological and functional indicators

Data from functional lung studies are used to parameterize respiratory mechanics models (Fig. 2), including:

- spirometry;
- plethysmography;
- gas exchange parameters;
- respiratory volume and respiratory rate parameters.

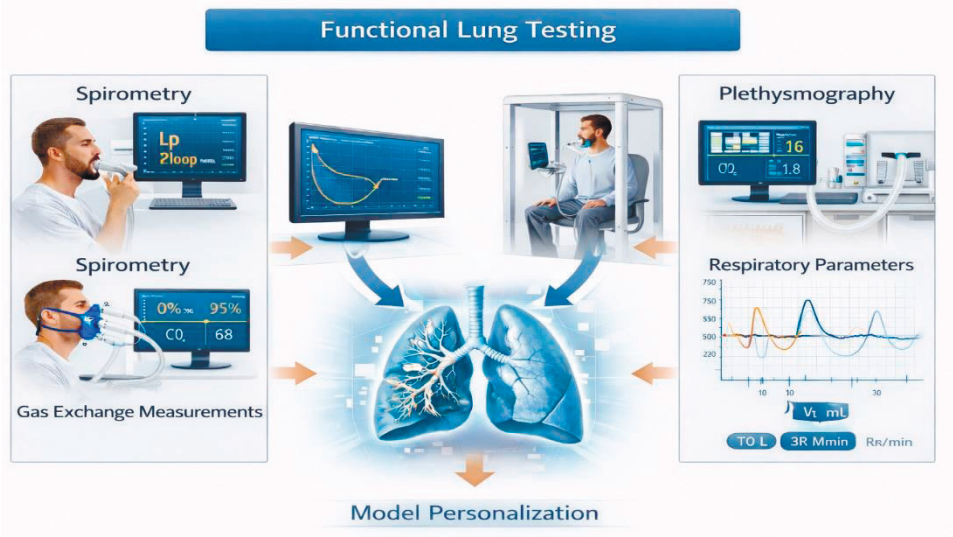


Fig. 2. Parameterization of respiratory mechanics models

These data allow determining the individual characteristics of the patient's respiratory system and adapting the parameters of the digital model [13].

3. Clinical data of patients

An important component of the digital twin is clinical data (Fig. 3), including:

- the patient's age and anthropometric parameters;
- history of respiratory system diseases;
- laboratory test results;
- respiratory therapy parameters.

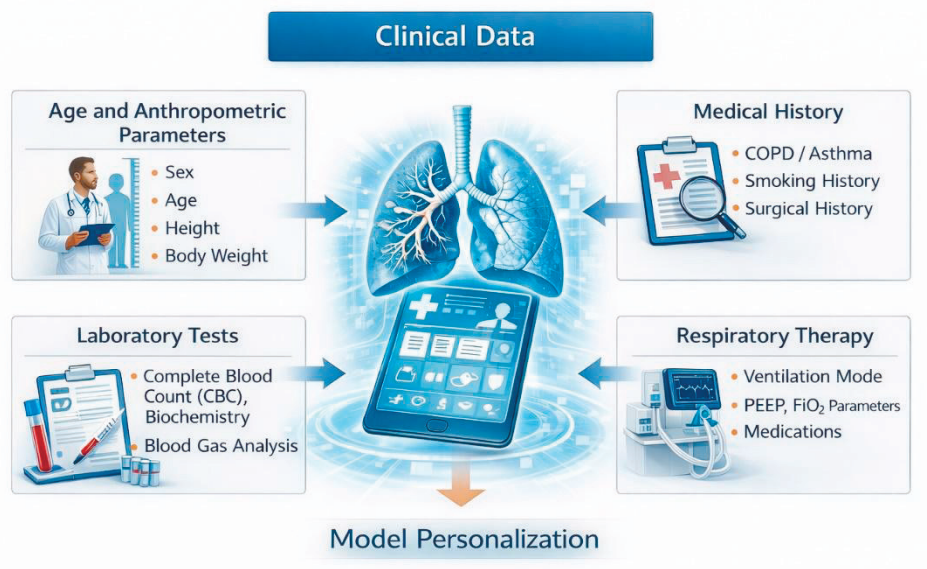


Fig. 3. Clinical data

The use of such data allows the creation of personalized models of the respiratory system and takes into account the individual characteristics of patients [9].

The creation of a digital twin of the lungs is based on the use of various methods of mathematical and computational modeling.

1. Biomechanical modeling of lung tissue

Models based on the principles of continuum mechanics are used to describe the mechanical properties of lung tissue. Such models allow analyzing the deformation of lung tissue during breathing, as well as assessing the distribution of stress and pressure in different areas of the lungs.

Biomechanical models take into account parameters such as:

- elasticity of lung tissue;
- resistance of the airways;
- lung compliance;
- pressure in the pleural cavity.

These processes are described mathematically using differential equations and numerical solution methods [12].

Let us consider a simplified model of lung tissue (Fig. 4) as an elastic material with elasticity E and viscosity η. During inhalation, the lungs expand, and the pressure distribution $P(x,t)$ along the airways is described by the force balance equation:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot (\sigma) + f$$

where:

- u is the deformation of the lung tissue;
- ρ is the tissue density;
- σ - stress tensor, taking into account elasticity and compliance;
- f - external forces, including pressure in the pleural cavity.

This model allows predicting:

- lung tissue deformation during inhalation and exhalation;
- stress distribution in different segments of the lungs;
- the effect of changes in compliance and airway resistance on ventilation.

An example of numerical implementation: when modeling the breathing of a patient with COPD, the decrease in lung tissue elasticity (E↓), the increase in airway resistance (R↑), and changes in pressure in the pleural cavity are taken into account. Numerical methods (e.g., finite elements) can be used to obtain the distribution of deformation and pressure across the lungs, which allows the parameters of artificial ventilation to be adapted to a specific patient.

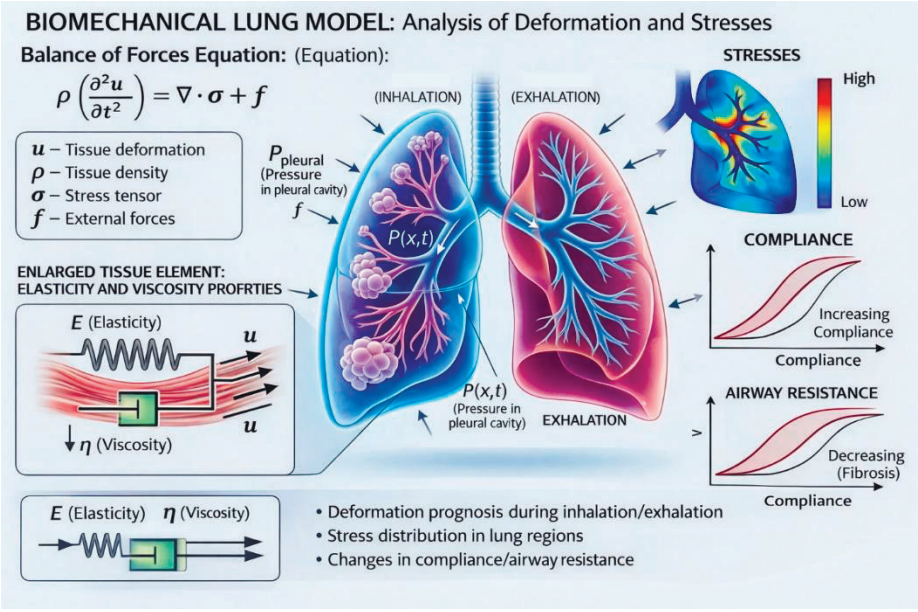


Fig. 4. Biomechanical model of the lungs

2. Airflow modeling

One of the key components of a digital twin of the respiratory system is the simulation of air movement in the airways. **Computational fluid dynamics (CFD)** methods are used for this purpose.

CFD modeling allows you to:

- analyze the distribution of air flow velocities;
- assess the turbulence of air flows in the bronchial tree;
- model the transport of aerosol particles and drugs;
- investigate lung ventilation processes.

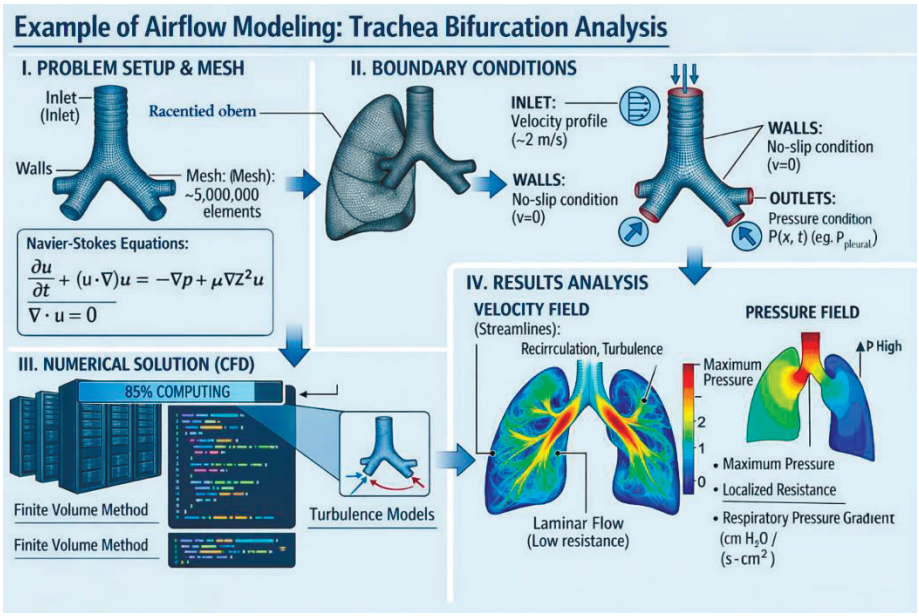


Fig. 5. Modeling of flow in the tracheal bifurcation

Calculations are performed based on the Navier–Stokes equations, which describe the motion of a viscous fluid or gas in space [2,5].

3. Multilevel modeling of the respiratory system

Modern digital twins of the lungs are based on **multilevel models** that combine several levels of organization of the respiratory system:

1. anatomical level (geometry of the respiratory tract);
2. physiological level (ventilation and gas exchange);
3. biomechanical level (lung tissue deformation);
4. system level (interaction between the respiratory and cardiovascular systems).

Such integration allows for more accurate reproduction of physiological processes and increases the predictive value of models [6,13].

As part of the study, a conceptual architecture for a digital twin of the respiratory system was developed, comprising three main components:

1. **Physical system** - the patient's actual respiratory system, the parameters of which are measured using medical devices and diagnostic methods.
2. **Digital model** - a virtual model of the respiratory system created on the basis of mathematical and computational algorithms.
3. **Data synchronization system** - a mechanism for exchanging information between the physical system and the digital model, ensuring real-time updating of model parameters.

For a clear representation of the model structure and data flows between components, it is advisable to refer to the diagram (Fig. 6):

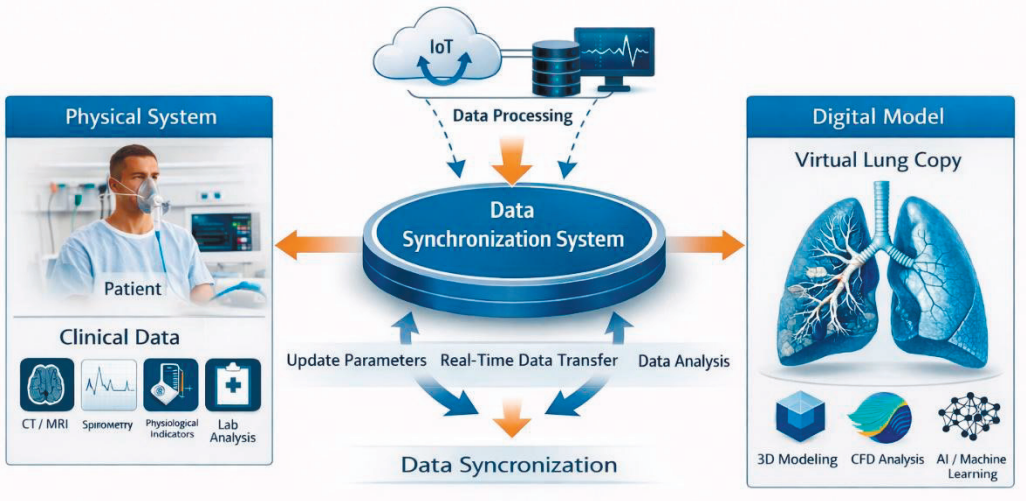


Fig. 6. Architecture of the digital twin of the human respiratory system

This architecture complies with modern principles of digital twin construction and provides the possibility of dynamic modeling of physiological processes [4,8].

The development of a digital twin of the respiratory system requires the formalization of a set of interrelated physiological processes that determine the functioning of the lungs. These processes include the movement of air flows in the bronchial tree, the deformation of lung tissue during breathing, and the processes of gas exchange between alveolar air and blood. Given the multiphysical nature of these phenomena, an adequate description of the functioning of the respiratory system is only possible based on the integration of models of aerodynamics, biomechanics, and diffusion transport of gases. In this regard, a mathematical model combining these physical and physiological mechanisms within a single computational structure is proposed for the construction of a personalized digital twin of the patient. Such a model allows describing the dynamics of lung ventilation, pressure distribution in the airways, tissue deformation, and gas exchange efficiency, which creates the basis for further numerical modeling and prediction of the state of the patient's respiratory system [6, 10, 12].

Taking into account the above provisions, a digital twin of the respiratory system can be represented as a formalized computational model reflecting the relationship between the main anatomical, mechanical, and physiological parameters of the lungs. In general terms, a digital twin of the lungs is defined as a dynamic system whose state depends on the geometry of the airways, airflow characteristics, mechanical properties of lung tissue, gas exchange parameters, and clinical monitoring data of the patient. Formally, this dependence can be represented by the following functional model:

$$DT_{lung}(t) = F(A, V, P, M, G, AI, t)$$

where

- A is the anatomical model of the bronchial tree
- V is lung ventilation
- P is the pressure distribution
- M - lung tissue mechanics
- G - gas exchange
- AI - machine learning module
- t - time

Thus, a digital twin is a multi-component multiphysical system.

Air movement in the respiratory tract is described by the Navier–Stokes equation:

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+(\vec{u}\cdot\nabla)\vec{u}\right)=-\nabla p+\mu\nabla^2\vec{u}+F$$

where
- $\vec{u}$ is the air flow velocity
- p - pressure
- ρ - air density
- μ - viscosity
- F - external forces

Continuity condition:

$$\nabla\cdot\vec{u}=0$$

This allows modeling **the distribution of air flow in the bronchial tree.**
Tissue deformation is described by the elasticity equation:

$$\sigma=E\varepsilon$$

where
- σ - stress
- E - Young's modulus of lung tissue
- ε - relative deformation

Lung volume dynamics:

$$V(t)=V_0+\Delta\,\mathrm{Vsin}(\omega t)$$

where
- V_0 - functional residual capacity
- ω - respiratory rate

Pressure in the respiratory system:

$$P_{alv}=P_{atm}-R\cdot Q-E_lV$$

where
- P_{alv} - alveolar pressure
- P_{atm} - atmospheric pressure
- R - airway resistance
- Q - air flow
- E_lV - lung elasticity

The diffusion of oxygen and CO_2 is described by Fick's law:

$$J=-D\nabla C$$

where
- J - gas flow
- D - diffusion coefficient
- C - gas concentration

Oxygen transfer rate:

$$V_{O_2}=D_L\left(P_{AO_2}-P_{cO_2}\right)$$

where
- D_L - diffusion capacity of the lungs
- P_{AO_2} - alveolar oxygen pressure
- P_{cO_2} - blood oxygen pressure.

A machine learning model is used to predict the patient's condition:

$$S(t+1)=f(X_t,\theta)$$

where
- S is the patient's condition
- X_t - vector of physiological parameters
- θ - parameters of the neural network.

General system of equations:

$$\begin{cases} \rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} \\ \sigma = E\varepsilon \\ P_{alv} = P_{atm} - RQ - E_l V \\ J = -D\nabla C \\ S(t+1) = f(X_t, \theta) \end{cases}$$

This system describes:

- the aerodynamics of breathing
- lung tissue deformation
- gas exchange
- prediction of the patient's condition.

The system is solved using an iterative multiphysics method**,** including:

1. CFD modeling of air flow [2,5];
2. FEM modeling of tissue deformation [12];
3. solving the diffusion equation;
4. integration with the AI module.

The structure of the model in this case is as follows (Fig. 7):

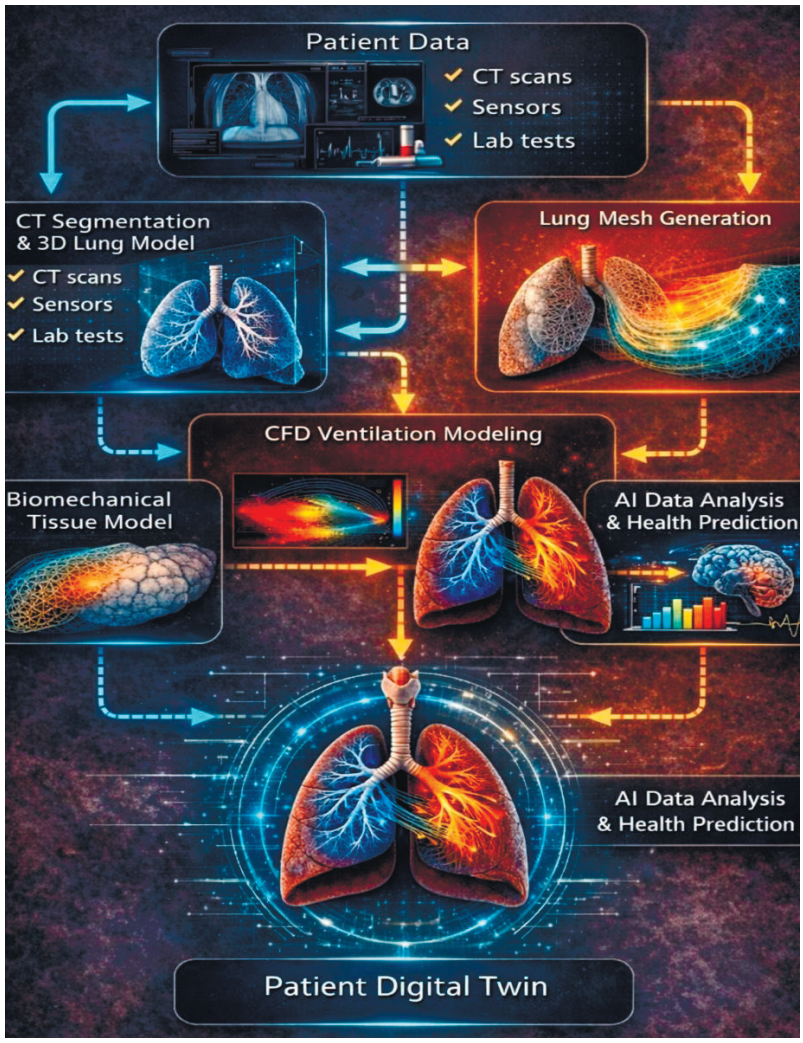


Fig. 7. Structure of the digital twin model of the respiratory system

The proposed model is distinguished by the following features:

1. it combines CFD modeling and lung biomechanics [2,5,12];
2. it takes gas exchange into account [6,12];
3. it integrates artificial intelligence algorithms [3,7];
4. it forms a complete digital twin of the patient [4,8,9].

The following methods were used to analyze the simulation results:

- statistical analysis;
- numerical modeling [10,12];
- visualization of three-dimensional models of the respiratory system;
- comparative analysis of various ventilation parameters [13].

The use of a comprehensive approach to data analysis allows us to evaluate the effectiveness of various models of the respiratory system and identify the most promising areas for their application in clinical practice.

Results and discussion.

The results of the study demonstrate the significant potential of using digital twin technologies to model the physiological processes of the respiratory system and optimize the diagnosis and treatment of lung diseases. Analysis of modern engineering and biomedical approaches has made it possible to identify key areas of application for digital twins in pulmonology, including modeling of respiratory mechanics [5, 12, 13], analysis of airflow in the respiratory tract [2, 5], and predicting the effectiveness of respiratory therapy [3,11].

One of the most important results of the development of digital technologies in medicine is the ability to create personalized three-dimensional models of the human respiratory system [8, 9] based on medical imaging data. The use of computed tomography and image segmentation methods allows the formation of detailed geometric models of the trachea, bronchial tree, and alveolar structure of the lungs [2].

The resulting anatomical models serve as the basis for further computational analysis and allow for the simulation of lung ventilation processes (). Within the framework of a digital twin, such models can be used to analyze the distribution of air flows in various parts of the respiratory system and to assess the impact of pathological changes on ventilation processes [3,13].

Recent studies show that the use of digital lung models can identify regional ventilation disorders that are difficult to detect using traditional diagnostic methods. For example, in chronic obstructive pulmonary disease (COPD), there is an uneven distribution of airflow and reduced ventilation in certain segments of the lungs, which can be detected using computational modeling [3,5].

One of the key areas of application of digital twins in pulmonology is the simulation of air movement in the airways using computational fluid dynamics (CFD) methods. These methods allow us to study the dynamics of air flows, pressure distribution, and air turbulence in the trachea and bronchial tree [2,5].

CFD modeling allows us to obtain quantitative parameters characterizing the processes of breathing, including:

- air flow velocity in different parts of the respiratory tract;
- pressure distribution during inhalation and exhalation;
- the degree of turbulence of air flows;
- features of aerosol transport of drugs.

The results of such models show that the geometric features of the respiratory tract significantly affect the nature of air movement. Even small changes in the diameter of the bronchi or the presence of inflammatory processes can significantly alter the aerodynamics of the respiratory tract and lead to a decrease in the efficiency of lung ventilation [5].

In addition, CFD modeling is actively used to analyze the effectiveness of inhaled drug delivery. Digital models allow predicting the distribution of aerosol particles in the airways and evaluating the effectiveness of various methods of inhalation therapy [2,10].

One of the most promising areas of development for digital technologies in pulmonology is the creation of individual digital twins of patients [3, 8, 9]. Such models are formed based on the integration of anatomical data, physiological indicators, and clinical information about the patient's condition.

Personalized digital models of the respiratory system allow virtual experiments to be conducted, including:

- modeling of various breathing modes;
- analysis of the effects of drug therapy;
- prediction of the development of pathological processes;
- optimization of artificial lung ventilation parameters.

For example, during respiratory therapy, a digital twin can be used to select the optimal parameters for artificial lung ventilation, which reduces the risk of ventilation-induced damage to lung tissue [6,11].

Such technologies are particularly relevant in the treatment of patients with severe respiratory diseases, such as acute respiratory distress syndrome, viral pneumonia, and chronic lung diseases [5,11].

Modern digital twins actively use machine learning and artificial intelligence methods, which allow for the analysis of large volumes of medical data and improve the accuracy of physiological process modeling [3, 7, 9].

Machine learning algorithms can be used for:

- automatically segmenting medical images;
- predicting disease dynamics;
- optimizing respiratory system model parameters;
- identifying hidden patterns in clinical data.

The integration of artificial intelligence with digital twins allows the creation of adaptive models that can be updated as new data on the patient's condition becomes available [3,8].

Analysis of current scientific research shows that digital twin technologies have significant potential to transform clinical practice in pulmonology. Their use can contribute to the development of personalized medicine [9], improve diagnostics, and increase the effectiveness of treatment for respiratory diseases.

In countries with developing healthcare systems, including the Republic of Uzbekistan, the introduction of digital technologies can be an important tool for improving the quality of medical care [1]. The use of digital twins can contribute to the development of telemedicine, remote patient monitoring, and the optimization of medical institutions.

In addition, the development of digital models of the respiratory system opens up new opportunities for scientific research, medical education, and the development of innovative methods for the diagnosis and treatment of lung diseases [7,10].

Thus, the results of the study confirm that digital twins are a promising technological platform for modeling the physiological processes of the respiratory system. Their further development and integration into clinical practice can significantly improve the effectiveness of diagnosis and treatment of respiratory diseases, as well as contribute to the development of modern digital medicine.

Conclusion.

This paper provides a comprehensive analysis of modern approaches to the creation and application of digital twins in pulmonology, including the study of engineering methods, mathematical and CFD modeling, and the integration of medical imaging and artificial intelligence algorithms. The results of the study confirm that digital twins are a promising platform for

personalized modeling of physiological processes in the respiratory system, allowing to predict the dynamics of diseases, optimize the parameters of respiratory therapy, and improve the effectiveness of clinical decisions.

The scientific novelty of the study lies in the systematization of engineering and biomedical methods for constructing digital models of the lungs, as well as in the formation of a conceptual architecture for a digital twin that integrates medical imaging data, physiological indicators, and clinical information about the patient. This approach ensures dynamic adaptation of the model to changes in the patient's condition, which significantly improves the accuracy of predictions and the effectiveness of virtual experiments.

From a practical point of view, digital twins of the respiratory system can be used for:

- personalized diagnosis and treatment of respiratory diseases;
- optimizing the parameters of artificial lung ventilation and non-invasive respiratory support;
- predicting the risks of complications in chronic and acute lung diseases;
- planning inhalation therapy and drug delivery to the respiratory tract.

The introduction of digital twin technologies is particularly relevant in the context of the digitalization of healthcare in the Republic of Uzbekistan, where national programs are aimed at introducing innovative technologies into clinical practice. The use of digital models of the respiratory system can contribute to the development of telemedicine, remote patient monitoring, improved diagnostic accuracy and treatment effectiveness, as well as the creation of a scientific basis for further research in the field of digital medicine.

Despite significant achievements, methodological and technical limitations remain, including the need to integrate heterogeneous data, high computational costs, model standardization, and clinical validation. A promising area for further research is the development of adaptive digital twins capable of updating model parameters in real time based on new patient data, as well as the integration of multi-organ models for comprehensive analysis of physiological processes.

Thus, digital twins of the respiratory system are an important tool for the development of precision medicine and innovative pulmonology, opening up new opportunities for personalized treatment, improving the quality of medical care, and integrating modern computing technologies into clinical practice both internationally and in the Republic of Uzbekistan.

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